THE FORMATION OF PORE ICE

IN COARSE GRAINED SOILS

by

Walter Fourie

RECOMMENDED:

Committee member

Advisory Committee Co-Chair

Advisory Committee Co-Chair

Chair, Department of Civil and Environmental Engineering

APPROVED:

Dean, College of Engineering and Mines

Dean of the Graduate School

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Walter Fourie

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ABSTRACT

Understanding the formation of pore ice in coarse grained soils is important to geotechnical and geo-environmental projects such as the construction of roads, airstrips and gravel foundations as well as the treatment of contaminated soils in the arctic, sub-arctic, alpine and northern regions. The amount of pore ice present controls the strength characteristics of the soils as well as the flow of fluid through the soil. Tests have been conducted to qualify the impact of gradation, temperature, compaction and initial moisture content on the formation of pore ice in coarse grained soils. The purpose of this study was to prepare a conceptual model of the freezing mechanism in coarse grained soils and to qualify the parameters that influence the ice formation. Results from this study indicate that the presence of fine grained particles in a coarse grained soil greatly impact the depth at which the pore space initially becomes saturated with ice. A conceptual model was developed and its application is shown with regards to the process of thaw weakening in roads and the creation of preferential flow paths in permeable reactive barriers.

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INTRODUCTION

The formation of pore ice in coarse grained soils is important to geotechnical and geo-environmental applications in cold regions. Drainage of liquids through frozen soils is limited by the formation and presence of ice in the porous matrix in comparison to similar unfrozen soils. As water added to the soil by rain events or by melting snow drains through a frozen soil, a fraction of the water will be retained in the pore space and eventually freeze. Ultimately, with repeated infiltration of water, the pore space will become saturated with ice, restricting any additional infiltration of water. Resulting high pore water pressures that may develop as the ice saturated soil thaws can results in geotechnical challenges such as the compromise in structural integrity of pavements – a process known as thaw weakening.

The infiltration of non-aqueous phase liquids (NAPLs, for example petroleum) accidentally released to the ground surface will also be impacted by the presence of ice in the pore space. Proper assessment and cleanup of these impacted regions first requires a better understanding of how pore ice changes the characteristics of porous media. In addition, others are investigating the use of permeable reactive barriers to control the migration of surface and subsurface contamination in cold climates (Snape et al., 2001). Design of these barriers requires an understanding of where ice is likely to form in the pore space and if preferential channels for flow will form due to the presence of ice. The purpose of this study was to develop a conceptual model of ice formation in coarse grained soils and to qualify the key parameters that influence the pore ice formation. The key parameters are: soil gradation, initial soil temperature at time of melt water infiltration, initial soil moisture content and soil compaction. Infiltration column studies were conducted and the results from these tests were used to develop the conceptual model of melt water drainage through frozen coarse grain soils. X-ray computed tomography of the frozen columns was used to support the results and the conceptual model.

BACKGROUND

To develop a conceptual model of pore ice formation in frozen coarse grain soils, the mechanisms that control the retention of water in unfrozen soils need to be understood. Two mechanisms control the retention of water in soils; adsorption and capillarity. Adsorption of water onto soil grain surfaces results from the attraction of polar water molecules to charged particle surfaces and the ions adsorbed on these surfaces. In coarse soils adsorption is most likely a minor contribution to water retention. The dominant water retention mechanism in this type of soil is capillarity. Capillarity results from the surface tension of water and its contact angle with the solid particles. In partially saturated soil, curved menisci form at the interface between water and air contained in the pore space. A simplified balance of interfacial forces in a pore space containing water and air results in the Laplace equation of capillarity.

$$P_a - P_w = P_c = \sigma\left(\frac{1}{r_1} + \frac{1}{r_2}\right) \tag{1}$$

In Equation (1), P_a is atmospheric pressure (conventinally taken as zero), P_w is water pressure in the pore space, P_c is capillary pressure, σ is the fluid-fluid interfacial force, r_1 and r_2 are the principal radii of curvature of any point on the meniscus. The quantity $(1/r_1 + 1/r_2)$ is often referred to as the mean curvature of an interface at a point. Mean curvature is affected by pore shape as well as pore size. Water and air contained in small pore spaces will have small mean curvatures. For purposes of this study, the most important aspect of this equation to note is the inverse relationship between capillary pressure and mean curvature. These two mechanisms are illustrated in Figure 1.

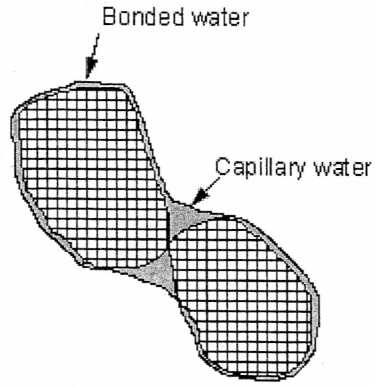


Figure 1: Water in unsaturated soil is bound to the soil surface and held by capillary forces

As water drains out of pore space in a soil, capillary pressures increase and the interfaces between air and water retreat to positions in the soil's pore space having smaller dimensions, so that the mean curvatures are smaller. Referring to Equation (1), the amount of water contained in a soil is a function of the capillary pressure. For a representative volume of soil, the relationship between capillary pressure and water content follows the general trend shown in Figure 2.

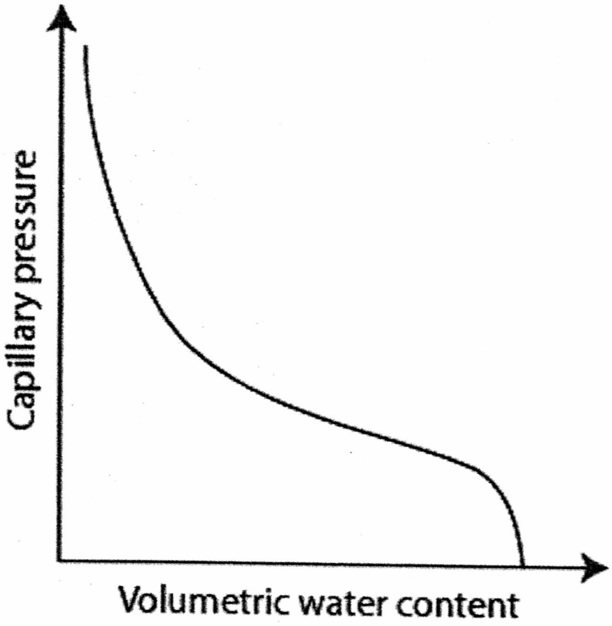


Figure 2: Soil-moisture curve for a typical soil

Considering drainage of a saturated soil, the trend shown in this figure indicates that at any particular capillary pressure water will be contained in the pore space with roughly a maximum mean curvature corresponding to that estimated using Equation (1) while the larger pores will be drained. The shape and range of the curve is controlled by the grain size distribution and structure of the soil. Soil with a wide range of grain sizes and thus pore sizes will result in a soil-moisture curve with a more gradual slope than a soil with a uniform pore size such as a sand.

Once drainage has ceased in soil with variable pore space dimensions the smaller pore spaces in the soil will contain water held by capillarity while the larger pore spaces will only contain adsorbed water. In coarse grain soil consisting of large dimensioned particles there is little small dimensioned pore space for the water to retreat. Once drainage has ceased in this type of soil the water is retained predominantly as adsorbed water.

Few studies have been conducted on infiltration and drainage in coarse soils and the effect pore ice formation and degradation has on geotechnical and geo-environmental applications. Permeability of frozen soils and the soil's ability to retain water has been the main objective of the previous studies on water movement through frozen coarse soils, but no available literature exists that characterize the formation of pore ice in these coarse soils.

Komarov (1957) studied permeability of frozen sand that had a porosity of 0.40 and water content over dry weight of 2 to 17% and pore ice saturation of 3 to 60%. Soil temperature prior to infiltration was -5°C and temperature of water infiltrating into the frozen sand was 0°C. During infiltration, the soil temperature increased to -2°C. Some ice was formed in the soil from infiltrated water. With a simple thermal balance, this researcher showed that the increase in ice saturation due to freezing infiltrating water varied from 0.05 to 0.1 (if heat exchange with the environment was restricted). He further speculated that saturation of soil with pore ice could be reached as a result of alternation of winter thaw and freeze periods.

Mukhetdinov (1984) examined the change in permeability in gravel with effective diameters ranging from 14 to 43 mm and the formation of infiltration ice. In these experiments, ice formed mainly in vertical veins. Baker and Hillel (1990) showed that infiltration into coarse soils overlain by a fine grained soil (at temperatures above $0^{o}C$) occurs by forming spatially distributed streams or fingers. This could partially account for Mukhetdinov's results.

Olovin (1993) studied the permeability of frozen coarse soils using air. Results from over 3000 tests generally showed that permeability decreased by approximately two to three orders of magnitude with an increase in saturation of up to 0.5. Overall the results from his studies showed that the permeability of a frozen soil is an uncertain parameter that depends on initial water content of the soil prior to freezing, soil temperature, and structure. It is interesting to note that in many of these tests the permeability of soil with pore ice saturations up to 0.2 were greater than the permeability of dry soil. Kaliuzhnyi and Pavlova (1981) also noticed this effect. These researchers hypothesized that the presence of unfrozen water on the soil particle surface accounted for the increase in relative permeability (Kaliuzhnyi and Pavlova, 1981). In multi-phase flow, such as in an air-water system, or air-water-NAPL system, the permeability of the different fluids is dependent on the saturation of all the constituents. Thus, in the experiments by Olovin and Kaliuzhhnyi and Pavlova the increase in permeability occurs because an interconnected water phase exists that increases the water permeability.

In contrast to the lack of data on ice formation in coarse soils, many studies have been conducted on ice formation in fine grained soils. It is also known that fine and coarse grained soils behave very differently with regards to freezing and thawing. Acknowledging this fact, characteristics of infiltration and drainage in frozen fine grain soils can help explain infiltration and drainage in coarse soils. One such study by Kaliuzhnyi and Pavlova (1981) studied formation of snowmelt losses by infiltration in a field study on fine grained soils. They found that the soil moisture content prior to freezing had a significant impact on the formation of an impermeable layer in soil due to water infiltration during a freezing season. At an experimental water balance station near Moscow, Russia, an impermeable layer formed in the soil during 10 years of the 17-year study. Kane and Stein (1983) also showed in a field test that the high water retention characteristics of fine grained soil (predominantly silt) resulted in high pore ice saturation near the ground surface.

Infiltrating water in some cases is not the only source of water for pore ice formation in a coarse grained soil. Ablimational ice (formed from the direct phase transition of vapor to solid) is formed from water vapor from the sublimation of ice (the direct transition of solid to vapor) or evaporation of water found deeper in the soil horizon. Vapor flow in frozen soils is induced by a temperature difference. The vapor pressure of the moisture is that over ice, since if there is unfrozen water available, that water is in equilibrium with the ice. Giddings and LaChapelle (1962) discuss this process in detail. Others have investigated the relative contributions of vapor flow and liquid water migration to the overall soil-water movement in frozen soils. Smith and Burn (1987) proved that moisture movement through frozen soils (a silty loam and a silty clay loam) as measured by moisture traps, overestimate the diffusion coefficient by orders of magnitude. They hypothesize that the vapor harvested in the traps are due to liquid water movement induced by a temperature gradient and not vapor flow. This hypothesis is in accordance with laboratory work done by Dirksen and Miller (1966), where they conducted experiments in moist, closed system soil columns. A temperature gradient was applied over the fined grained soil columns and moisture migrated from the unfrozen zone to the frozen zone at such an extent that could not be attributed to only vapor flow. However, in coarse grained soils, a study by Jackson (1965) concluded that vapor flow is the predominant mechanism, while liquid movement is negligible. Most likely these results are due to a lack of unfrozen water and a low capillary pressure gradient present in frozen coarse grain soils. Research done by Nakano et al. (1984) supports the belief that vapor transport plays a significantly role in dry soils, but that the vapor flow becomes insignificant as the pore ice volume increases decreasing the permeability of the soil to vapor flow. Goering and Kumar (1994) showed by simulation that highly porous embankments induced a large enough airflow to significantly alter the thermal regime of the underlying ground, which would increase vapor flow under these conditions. From work done by Ostromouv (2004) and Lipenkov (1989) it is indicated that ice sublimation and ablimation can move ice inclusions through the soil. From these studies it can therefore be hypothesized that, in coarse soils, vapor flow and the subsequent formation of ablimational ice could have a significant effect on the infiltration of melt water.

In a study on pavement performance, Eigenbrod and Kennepohl (1996) investigated the accumulation of ablimated ice at the interface between asphalt pavement and coarse road base. The results of these researchers' field and laboratory studies showed that under certain temperature conditions water accummulates at the pavement – road base interface. Ambient air temperature in these tests varied from 5 to -15°C, which allowed thawing of sublimated ice and formation of infiltration ice; however, this effect was not mentioned nor studied by these researchers.

METHODOLOGY

The formation of pore ice was examined in one-dimensional column studies. The infiltration studies were conducted in a large walk-in cold room to ensure a homogeneous temperature distribution through the columns. In studies conducted on fine grained soils it is common to establish a temperature gradient across the sample to induce soil freezing, frost heave and water migration. However, in the case of coarse grained soils, the moisture will not migrate by capillary force and the only gradient for water movement will be that induced by gravity or by vapor flow. The columns were constructed of clear acrylic to allow a visual interpretation of the results. The mesh at the bottom of the column has a screen size of 1.5mm. The setup is shown in Figure 1.

In each test, melt water at 0°C was introduced at the top of the column and allowed to infiltrate and freeze. Melt water that drained to the bottom of the column was collected in a reservoir. Collected melt water was allowed to freeze prior to the introduction of the next volume of melt water so as to reduce the possibility of a convection current between the water in the reservoir and the bottom of the column. Between each introduction of melt water the column and the reservoir were weighed to establish the mass of water retained in the column. The entire setup was also enclosed in a loose plastic wrapping to minimize evaporation and ice sublimation out of the column.

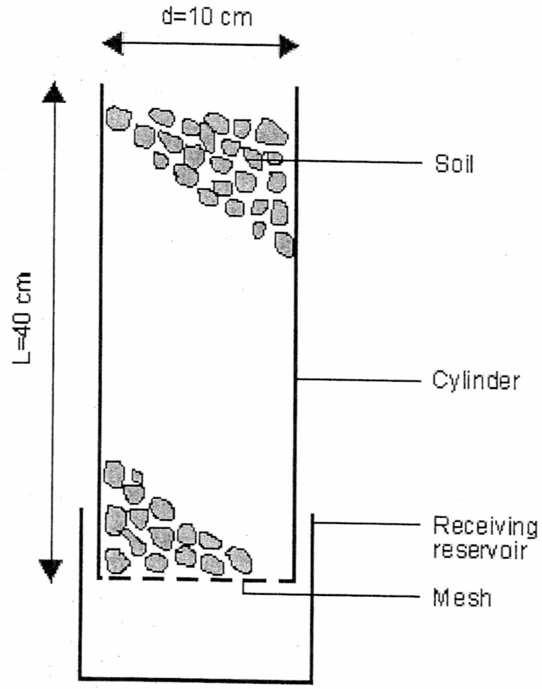


Figure 3: Cross sectional view of column used in study.

Parameters varied in the column studies were soil composition, soil temperature, volume of water added by infiltration, soil compaction and initial soil moisture content. Location of the initial impermeable zone created by ice saturated pore space and entrapped air (Figure 4) was documented for each set of soil properties tested.

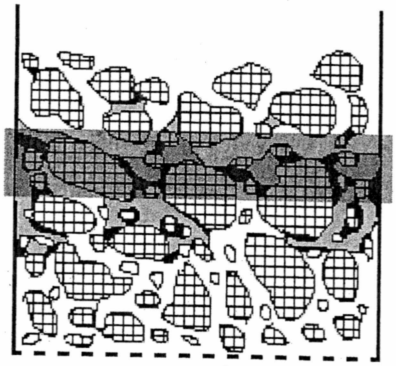


Figure 4: The initial impermeable ice layer forms when all possible paths for downward flow have been blocked off by pore ice. Gray areas represent unfrozen moisture and black areas are ice. Hatched areas are soil particles.

The coarse soils selected for the experiments were a well graded soil that could be used as a road surface coarse, a uniformly graded pea gravel with average particle diameter of 6.25 mm, and a uniformly graded coarse gravel with average particle diameter of 25 mm. By the USCS the well graded material would be a well graded gravel with sand. A photograph of the three soils is shown in Figure 5 and the particle distribution of the well graded soil is shown in Figure 6.

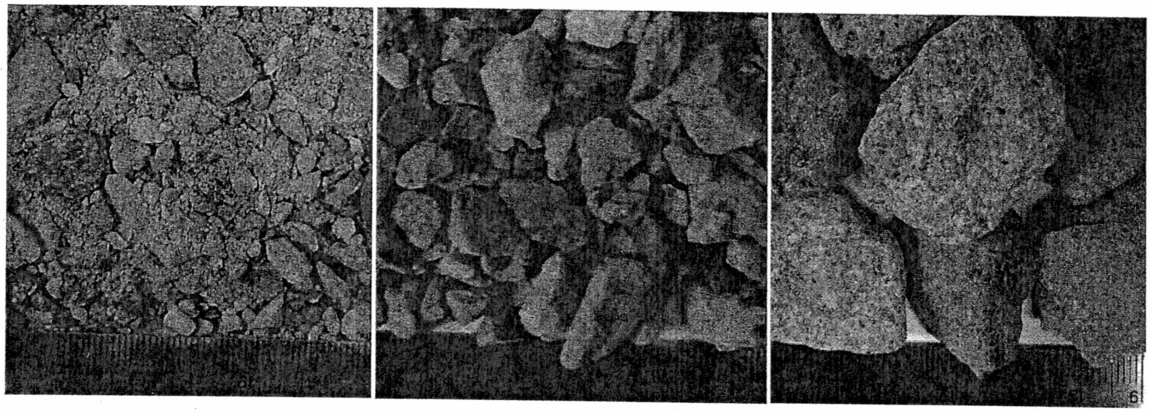


Figure 5: The three soil samples used in the tests. From left to right are the well graded gravel with sand, the pea gravel and the large gravel. Each picture is 6cm wide.

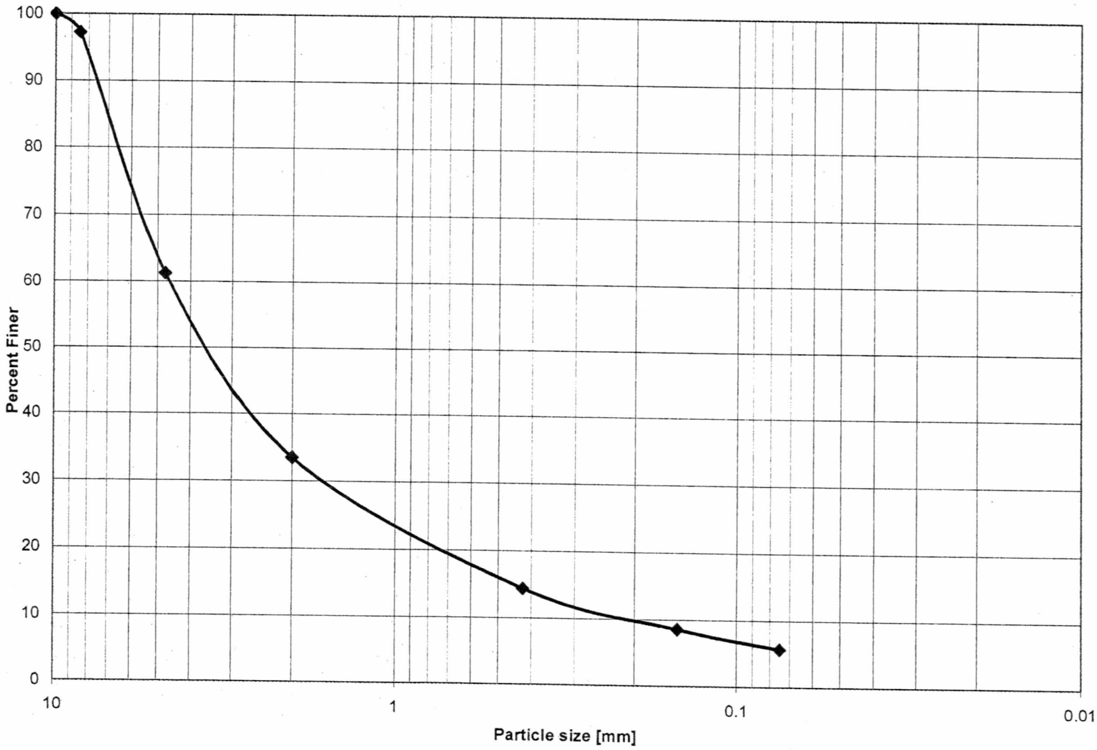


Figure 6: The particle size distribution of the well graded gravel with sand used in this study.

Summary of the tests conducted with these soils are shown in Table 1.

Table 1: Summary of the tests conducted

Test	Soil Type	Initial moisture content	Compacted	Soil Temperature	Volume of water Added
A	Large gravel	Dry	Not required	-10 °C	600 ml added in 50 ml increments
B	Pea gravel	Dry	Not required	-10 °C	600 ml added in 50 ml increments
C	Well graded gravel	Dry	Compacted	-2 °C	80 ml added in 20 ml increments
D	Well graded gravel	Dry	Compacted	-5°C	80 ml added in 20 ml increments
E	Well graded gravel	Dry	Not compacted	-10 °C	400 ml added in 50 ml increments
F	Well graded with fines (<75μm) removed	Dry	Compacted	-5 °C	120 ml added in 20 ml increments
G	Well graded gravel	4.5%	Compacted	-5°C	60 ml added in 20 ml increments
H	Well graded gravel	9%	Compacted	-5°C	40 ml added in 20 ml increment
I	Well graded gravel	Dry	Compacted	Room Temperature	80 ml added in 20 ml increments

The well graded soil was compacted to 90 - 95% of its maximum dry density, which was determined to be 2.1 g/cm^3 as found by the standard compaction test, D698 - 91 (ASTM, 2000). The soil was oven dried at 110°C for 24 hours before each experiment, except where mentioned otherwise.

In addition to the infiltration studies, X-ray computed tomography was used to examine the columns. Smaller columns with a diameter of 69mm were used, as the scanner had a sample size limitation. The soil used for these studies were the well graded sample and they were sequentially infiltrated with 10 ml of melt water.

RESULTS AND DISCUSSION

The parameters that impact the formation of pore ice after repeated infiltration with melt water that were investigated in this study are: soil gradation, soil temperature, infiltration volume, compaction and initial moisture content. The impact of each of these parameters on pore ice formation was tested and in each test the location of the initial pore ice blockage was identified. Generally, the columns either became saturated with pore ice from the screen at the bottom of the column upwards, or an ice-saturated layer formed near the top part of the column, while the bottom of the column remained dry. A summary of the results for each test are shown in Table 2.

Gradation

The gradation proved to be an important parameter as to the location of the initial ice layer. Infiltration of melt water into the large gravel and pea gravel (tests A and B) resulted in an ice layer forming at the bottom of the column where it encountered the mesh. The melt water flowed relatively unheeded through the large pore spaces of the gravel from the top of the column to the fine plastic mesh. Upon completion of gravity drainage through the column, a fraction of the melt water that reached the screen was retained by capillary forces in the relatively small sized mesh openings. This retained water eventually froze, blocking drainage pathways for subsequent additions of melt water.

Table 2: Results summary

Test	Result
A	Pores saturated with ice starting at the screened bottom of the column and progressing to the top of the column. Further infiltration of melt water was blocked after approximately 600 ml were added to the column.
B	Pores saturated with ice starting at the screened bottom of the column and progressing to the top of the column. Further infiltration of melt water was blocked after approximately 600 ml were added to the column.
C	Wetting front progressed to 4 cm with the first 20 ml added. Further infiltration of melt water was blocked after approximately 80 ml were added to the column.
D	Results similar to Test C.
E	Pores saturated with ice starting near the top of the column. Further infiltration of melt water was blocked after approximately 400 ml were added to column.
F	Pores saturated with ice starting near the top of the column. Further infiltration of melt water was blocked after approximately 120 ml were added to column.
G	Pores saturated with ice starting near the top of the column. Further infiltration of melt water was blocked after approximately 60 ml were added to column.
H	Pores saturated with ice starting near the top of the column. Further infiltration of melt water was blocked after approximately 40 ml were added to column.
I	Wetting front progressed to 8 cm with the first 20 ml added and progressed downward with each 20 ml addition.

Once an impermeable barrier of ice-saturated mesh openings was formed, pore space above the barrier became saturated with pore ice and entrapped air as additional volumes of melt water were added to the column.

In contrast to the large-diameter gravel and the pea gravel, the well graded gravel rapidly created a frozen barrier near the top of the column (Tests C through H). Only a small amount of melt water was needed in these tests to saturate the pore space with ice and entrapped air, blocking all drainage pathways. An explanation can be developed for this result by first noting the volume of melt water required to saturate the soil in Test D and F. With the fines (<75 μm) removed from the soil in Test F, the volume of melt water that was able to infiltrate into the frozen soil prior to drainage pathways becoming blocked increased by approximately 50%. It is therefore apparent that the presence of relatively smaller particles intermixed with coarse material greatly decreased the amount of melt water needed to block drainage pathways with pore ice. This phenomenon is illustrated in Figure 7. The amount of soil-water retained by capillary forces in soil after drainage is inversely related to the size of the pore. The addition of relatively smaller soil particles to an otherwise uniform coarse grain soil reduces the average pore size in the soil resulting in a greater amount of soil-water retained in the soil after drainage. In freezing soils, the retained water eventually freezes to ice further reducing pore size and eventually blocking drainage pathways for subsequent additions of melt water.

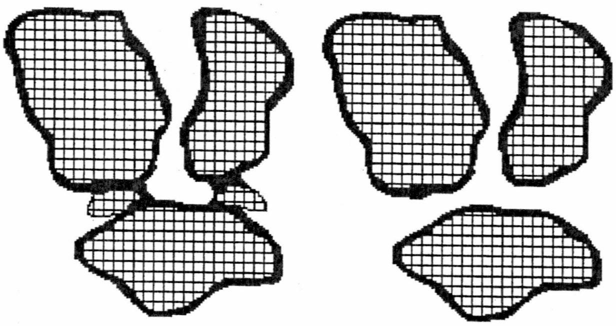


Figure 7: Comparison of pore ice formation in coarse grained soils with (a) and without (b) the presence of smaller particles. Cross-hatched areas represent soil grains and the solid areas represent water held by capillary forces. The scenario shown in (a) represents the creation of a dead-end pore with minimal pore ice content in comparison to the scenario shown in (b) where pore channels remain open to flow. Further additions of water to the pore space shown in (a) will result in the pore becoming either filled with ice or entrapped air.

Figure 8 shows a slice and profile view of a frozen infiltrated column, generated by an X-ray computed tomography scanner. In the profile view (at the bottom of the image), the crosshairs are centered on a dead end pore. The dark sections are the soil grains, the light gray is ice and the white sections represent air. It is apparent that there are thin films of ice retained on the soil boundaries, but where the large particle on the left of the crosshairs meet the smaller particle on the right, the pore space has been filled with ice. This is the same phenomena as shown in Figure 7. This image was generated by a

SkyScan 1076 *In vivo* instrument at a voxel size of 35 μm. The sample was 69 mm in diameter and the image is 35 mm in diameter.

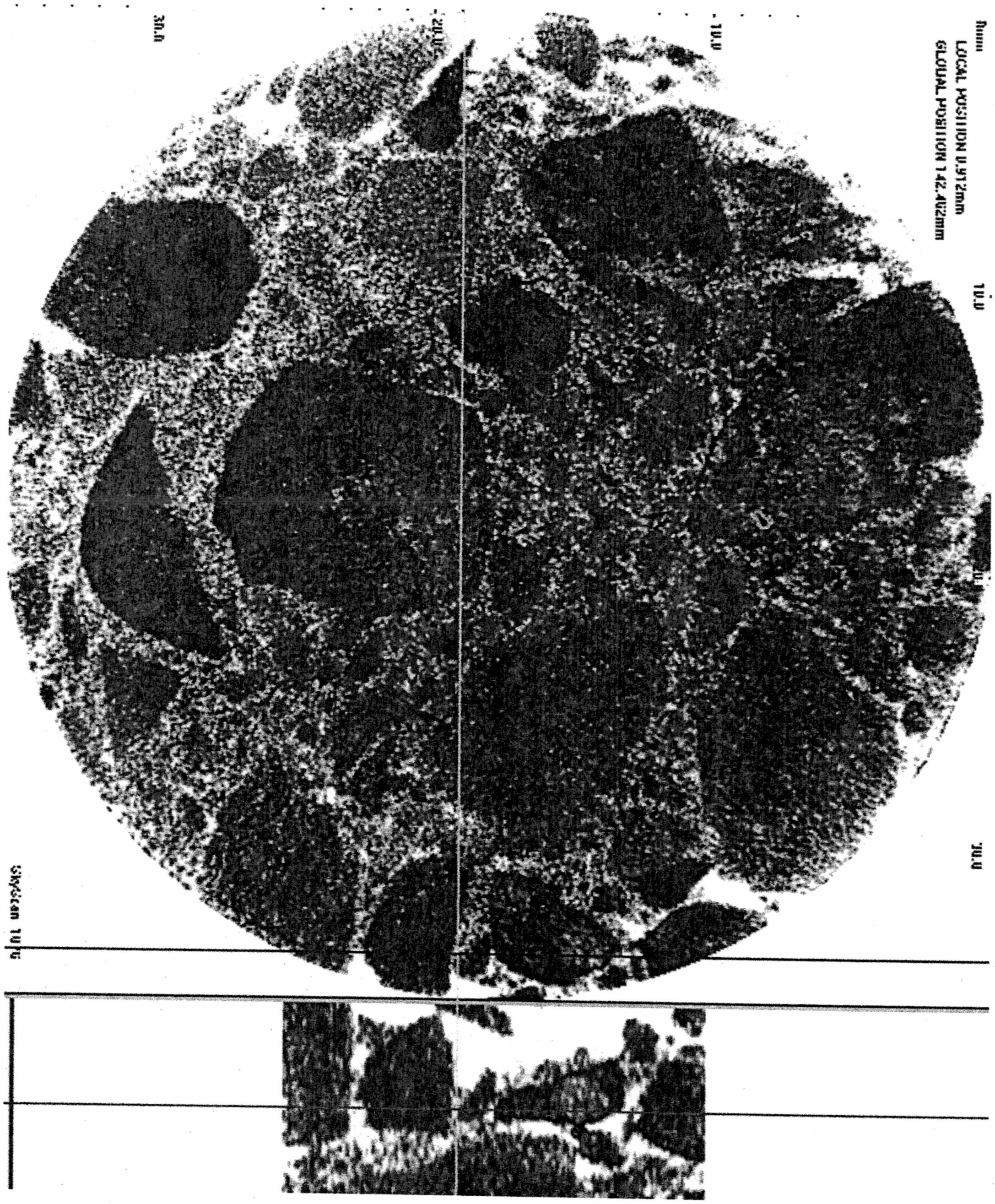
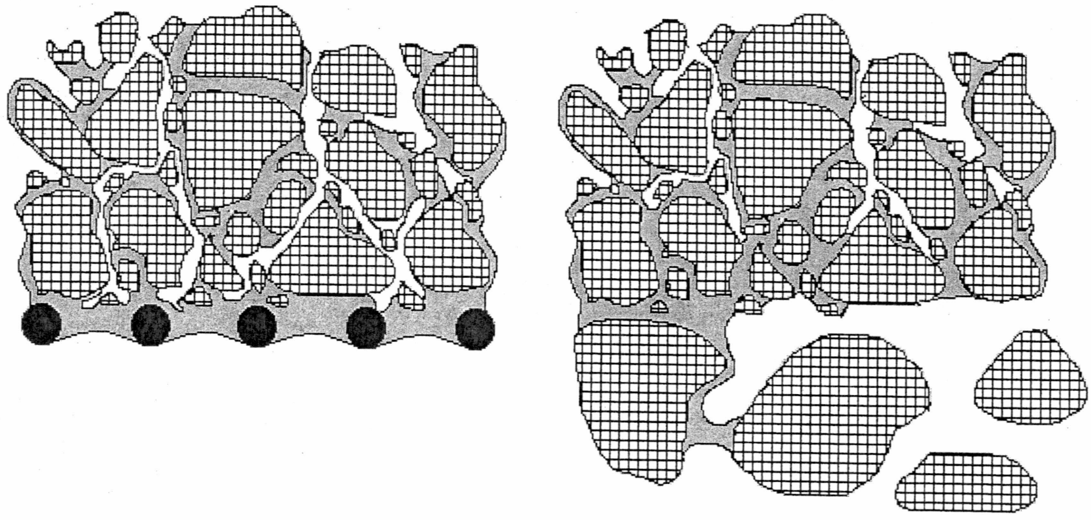


Figure 8: Section and profile CT images of a frozen infiltrated column

The retention of water at the mesh at the bottom of the column requires further discussion due to the similarity of this configuration to a layered soil of relatively large diameter particles underlain by relatively smaller particles.



(a) (b)

Figure 9: Water held by a capillary break freezes at the interface. In (a) the laboratory experiment is shown where water is infiltrated at the top, advances to the capillary break and is unable to pass, as the head is not greater than the suction pressure. The water freezes at this point and subsequent additions of melt water will pond on top of the impermeable layer. This can be likened to the real world situation in (b) where a gradation change takes place, as in the case of a surface course on top of a base course. Preferential flow paths may form at the gradation change.

A fraction of the water is retained at the bottom of the column as water passes through the relatively fine mesh. This fraction is retained due to the capillary break formed. In a real life situation this could occur in a layered soil system such as roadbeds. A schematically representation is shown in Figure 9. When there is an abrupt gradation change in a soil, the coarser layer serves as a barrier to water flow due to the relatively greater water entry pressure required for the water to flow into the coarser soil. Yang et.al. (2004) showed that in such a capillary break situation the finer soil above the capillary break will have volumetric water contents close to saturation. They studied this phenomenon by infiltration of water into sets of fine, medium and coarse sands. The water will be in storage until such a time as enough pressure is available for breakthrough to occur. Breakthrough occurs when the wetting fluid saturation in the overlaying relatively finer soil reaches such a value that the capillary pressure at the interface decreases to a value equal to the capillary pressure in the underlying coarser soil. This is shown in Figure 10. In freezing soils this phenomenon will give the water enough time to form ice at the interface.

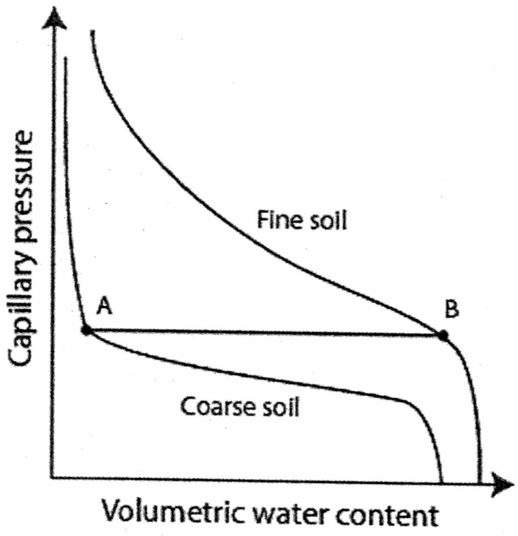


Figure 10: Breakthrough of a fine soil overlaying a coarse soil occurs when the capillary pressure in the fine soil (point B) is equal to the capillary pressure in the coarse soil (point A). At this point the fine soil will be nearly at saturation. The coarse soil will remain at point A (near or at residual saturation), until breakthrough occurs.

In studies done by Stormont and Anderson (1999) they showed that this process could happen repeatedly as the flow of fluid changes through the soil. They also showed that the higher the infiltration volume, the greater the reduction in capillary pressure in the overlaying finer soil above the interface. This reduction can be attributed to the water being retained by capillary forces the interface, and thus a capillary pressure gradient develops above the interface. In a freezing soil, this would mean that not only does the pore ice content increase at the capillary break interface, but also throughout the overlaying finer soil. Yang et.al (2004) and Stormont and Anderson (1999) both concluded that the capillary break is more effective with a uniform underlying layer, which at the extreme is represented by the empty space below the mesh in the columns discussed in this study.

Temperature

The column studies were conducted at -2 °C, -5 °C and -10 °C, with a control column at room temperature outside the cold room. The columns containing the compacted well graded soil in the cold room (Tests C-F) all formed an ice layer near the top of the column with the addition of 80-100ml of melt water. The infiltration depth of the first addition of melt water in the freezing columns was not significantly different between the columns at different sub-zero temperatures. These results would suggest that within the temperature range used in this study, the sub-zero temperature has relatively little influence on the location of the ice layer. This result may be due to the much larger value of the latent heat of water as compared to the specific heat of the soil. Heat flows from the melt water (which is relatively warm) into the soil matrix (which is relatively cold) until the latent heat of the water has been released. Heat transfer will continue until either the water has drained through the pore space or the temperature gradient needed for freezing has been lost (i.e. the soil temperature equals the melt water temperature).

In this study the control column that was kept at room temperature (Test I) exhibited a deeper penetration of water at any specific time. This result supports a hypothesis that in the freezing columns some water rapidly freezes to the soil surfaces, decreasing the dimensions of the pores and thus increasing the amount of water retained in the pore space. The smaller pores also increase the resistance to downward flow. With the formation of ice a smaller amount of water is available to travel downward under the influence of gravity. If such a mechanism were not involved, the initial infiltration into the freezing and unfrozen columns would penetrate the soil to the same depth.

In a no-flow situation Bronfenbrener and Korin (2002) showed that the time it takes for water to freeze from an initial moisture content to an equilibrium moisture content in a sandy loam would be an order of magnitude higher than in a sandy soil. The unfrozen water content in the different soils account for this large difference in freezing rates. The freezing rate is proportional to the difference between the initial moisture content and the equilibrium moisture content at a specific temperature. In a fine grained soil, the equilibrium moisture content is large, and hence the driving force is small. In a coarse grained soil the equilibrium moisture content (at a given temperature) is small and therefore the driving force, and hence the rate of crystallization, is large. This analysis further supports the theory that in a coarse grained soil (with very low equilibrium unfrozen moisture content) the water rapidly freezes to the soil grain boundary.

Compaction

The amount of water required to block infiltration was compared between the uncompacted and compacted well graded gravel (tests D and E, respectively). In test E, the well graded soil was compacted to 90-95% of its maximum dry density, which is about 2.1 g/cm^3. The compaction drastically decreased the amount of melt water needed to saturate the column with ice; approximately four times less water was needed to freeze the compacted soil in comparison to the amount required for the uncompacted soil. The compaction changes the pore throat diameters by forcing the soil grains closer together. It also forces fine particles to move into the larger pore spaces between bigger particles. The result of compaction is then the creation of relatively small dimensioned pores capable of retaining larger amounts of melt water. The results show that the soil becomes saturated with pore ice at a shallower depth in the compacted sample compared to the uncompacted sample.

Initial moisture content

Tests C, G and H were conducted on a dry soil and soils with 5% and 9% initial moisture content by weight. The columns were allowed to freeze before the melt water was introduced, and in subsequent additions of 20 ml of melt water, the columns formed a saturated ice layer with the addition of 80ml , 60 ml and 40 ml, respectively. The initial moisture (ice) content of the soil decreases the permeability of the soil and increases the melt water retention by decreasing the average pore dimensions. As expected, the greater the amount of pore ice in the soil prior to infiltration, the smaller the amount of melt water required to saturate the pores with ice.

Conceptual model

With the results from this study, a conceptual model of how the pore ice forms in coarse soils can be developed. As melt water imbibes into an initially dry frozen soil, heat flows from the water into the soil and a thin layer of water rapidly freezes to the soil grain surfaces. Dimensions of individual pores in the soil decrease with this addition of ice. In accordance with Equation (1), the reduction of pore dimensions increases the volume of water retained in the relatively small pore spaces after drainage ceases. This can be conceptualized visually in a water retention curve as shown in Figure 11. As the soil becomes saturated with the ice the porosity of the soil will decrease and the residual saturation will increase due to decrease in the pore diameters and the creation of dead end pores. It is important to note that the soil water retention curve, which is normally determined from equilibrium data, has now become a function of time as the pore space is being altered every time there is additional infiltration of melt water and subsequent formation of pore ice.

The formation of a film of ice is repeated every time additional melt water is added to the soil. Eventually drainage pathways through the soil become blocked with ice and dead end pores are created leading to the saturation of the pore space with ice. The creation of dead end pores also result in the entrapment of air in the pore space. Entrapped air reduces the volume of melt water required to saturate the available pore space with ice.

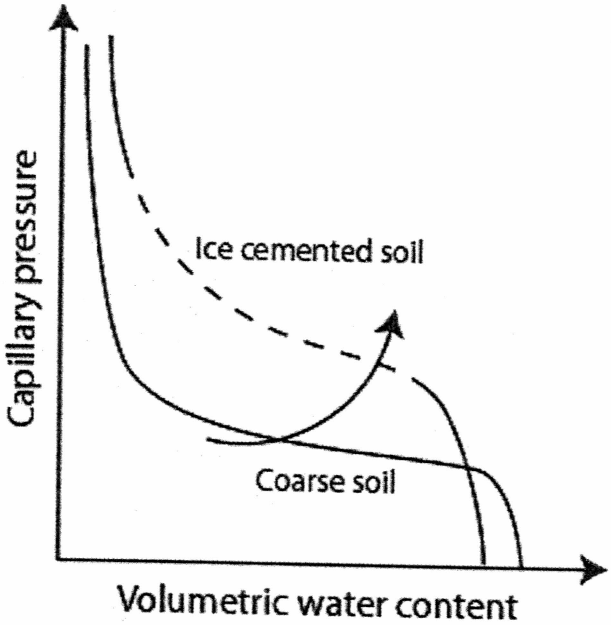


Figure 11: Change in the water retention characteristics as the coarse soil becomes cemented with ice. The ice cemented soil typically has a higher residual water content, a lower porosity and will retain more water at a given capillary pressure.

As the soil becomes increasingly saturated with pore ice with each introduction of melt water, the permeability of the soil decreases, slowing the drainage of melt water through the soil. With sufficient amount of pore ice in the soil a permeability will be reached such that complete drainage of the melt water will not be attained prior to the melt water freezing. The process of pore ice formation is shown in Figure 12.

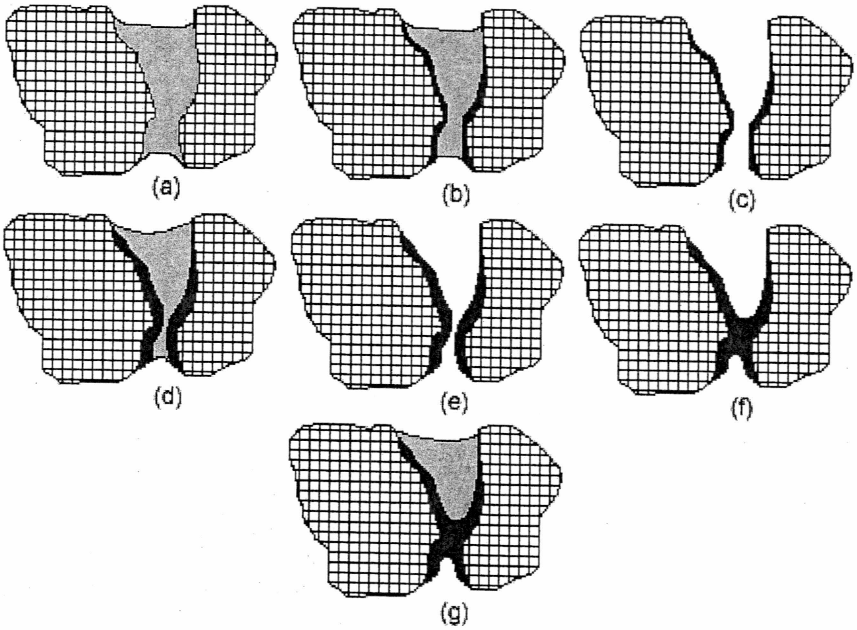


Figure 12: The hypothetical freezing of coarse grained soils from infiltration of melt water. In (a) the pore is filled with melt water. As water drains through the pore, a fraction of the water freezes to the pore walls (b) and then drains (c). Successive infiltration causes additional freezing to the pore walls (d) and (e) until the pore has been closed off (f). Thus the pore-throat has become a dead end that will eventually fill with ice (g).

As was shown in **Figure 7**, the process of creating dead end pores is exacerbated in a well graded soil owing to the existence of relatively small pore spaces prior to the introduction of ice. With the initial introduction of melt water into a frozen well graded soil, water is retained in the smaller pores forming ice and blocking drainage pathways. Additional dead end pores are created with each addition of melt water. Results from this study show that the pore space in well graded soils become saturated with ice at a relatively shallow depth below the soil surface in comparison to gravel that does not contain relatively smaller diameter particles.

What is uncertain is how the soil will behave as it drains (indicated by the dashed section in Figure 11). The drainage pathways may all drain sequentially with a small increase in capillary pressure with a decrease in pore diameter. Thus the water will be retained in smaller and smaller pore spaces as the soil fills up with ice, this would give the water retention curve a steeper incline. Or the primary drainage pathways may all decrease in diameter and drain at the same time through the preferential flow paths, which would give the water retention curve a flatter incline. At the moment there exists no experimental method to unequivocally determine the water retention curve for a frozen soil.

IMPLICATIONS

The formation or pore ice in coarse grained soils is an important concern in cold regions engineering with relation to the integrity of roadbeds, gravel pads, permeable reactive barriers and leach fields. In addition, the pore ice affects aqueous and non-aqueous fluid movement through the media, as well as physical properties such as its thermal conductivity and shear strength. The impact of pore ice formation on the performance of permeable reactive barriers and roadbeds will be briefly discussed.

Permeable reactive barriers

Permeable reactive barriers (PRBs) are a relatively new technology employed to treat groundwater contamination (EPA, 1998). The technique has become popular due to its low operating and maintenance costs as well as its efficient removal of contaminants. For PRB's in cold regions, Snape et.al. (2001) reported that a fine grained material is unsuitable, as it is difficult to handle and decreases rapidly in permeability during the freezing cycle of the active layer. In regions underlain by permafrost, the majority of the subsurface flow occurs in the active layer, and it is therefore essential that the PRB retains a reasonable permeability during the seasonal or diurnal freezing cycles. Snape reported that granulated activated carbon with nominal grain size of 0.5 – 1.4mm worked well in a test site on Antarctica.

As shown previously, a gradation change in a soil can induce the formation of preferential flow paths in the coarser material. For temperature regions, Kamolpornwijt et al. (2003) and Li et al. (2005) reported a change in the flow field in the vicinity of a PRB, which could cause a decrease in efficiency of the barrier as the fluid is conducted through preferential channels. In both the studies pore blockage by mineral precipitation was the main reason for preferential flow. In barriers subjected to freeze and thaw cycles, this effect will be exasperated as certain pores become blocked with ice. The introduction of finer materials into the coarse material of the PRB will facilitate the formation of pore ice and hence the creation of preferential flow channels. If the PRB becomes ice rich then the flow will become severely restricted and may bypass the barrier. The gradation change at the front end of the barrier may also hold up the water flow and allow the water to freeze, further decreasing the area open for flow and inducing the formation of preferential flow paths. In addition, Snape indicates that reactive material seems to physically break down due to freezing and thawing action creating smaller particles (personal communication, 2005). Hence, material that is prone to physical degradation may be original uniformly graded, but will eventually end up containing a range of particle sizes resulting in the creation of preferential flow paths as pore ice forms in the barrier.

Ostromouv (2004) speculates that hyper-continental climates, such as Antarctica, are also prone to the formation of ablimational ice layers. Thus, ice could be transported into the PRB by the convective cycling of sublimation and ablimation in the sub-surface. The greater the amount of pore ice in the barrier, the greater the reduction in efficiency.

Understanding the influence particle size gradation has on pore ice formation will aid in the design of these systems.

Road beds

The foundations of geotechnical structures, and specifically roads, are characterized by engineered soil layers of varying gradations. In northern regions it is important that these soils, if they are in the active layer, are not frost susceptible. Fine grained soils, or coarse grained soils with a large amount of fines present, will be susceptible to wicking and may cause frost heave. Most surface and base courses are therefore designed to minimize the probability of frost heave. However, the soil layer should still be stable, which necessitates the use of a well graded soil. Chamberlain (1981) showed statistically that gradation is the most important parameter with regards to a soil's frost susceptibility. As water infiltrates from the top, care should be taken that the gradation change between the different layers is small enough not to induce a significant capillary break. As discussed previously, such a capillary break would form an impermeable ice layer close to the road surface. A high percentage of fines near the road surface will also cause high ice saturations near the surface. During thawing, the ice saturated region will become over saturated with water and cause high pore water pressures. Moreover, the applied stress becomes significant when the temperatures in the soil are close to the melting point, as the resiliency modulus is strongly dependent on the unfrozen moisture content (Cole, et al., 1986). The thermal conductivity of the soil matrix is much higher than that of the ice and water, and therefore the first part to melt will be the ice in contact with the soil skeleton. This greatly impacts the strength of the subgrade. If a load is applied to the soil, such as the wheel of a car, the excess pore pressure and the weakened soil skeleton will cause rutting and cracking of the road surface. The subsequent consolidation and dissipation of the pore pressures can cause large settlements.

A coarse soil also facilitates the flow of vapor in the subgrade. It has been shown that coarse soils in embankments can significantly alter the ground thermal regime (Goering and Kumar, 1994) and that the vapor flow facilitates the condensation of water between the asphalt and the underlying granular base (Eigenbrod and Kennepohl, 1996). Such condensation and subsequent freezing can also attribute to the over-saturation of the subgrade.

CONCLUSIONS AND RECOMMENDATIONS

The freezing mechanism of pore ice is an important issue with regards to engineered coarse grained soils. In this study the parameters that influence the formation of pore ice were characterized. Columns packed with either a uniformly graded coarse soil or a well graded soil at sub-zero temperatures were infiltrated with melt water. The formation of pore ice in the columns were examined visually and with the aid of X-ray computed tomography. Results from this study showed that the addition of fine particles to a coarse grained soil decreases the average pore dimensions and drastically changes the location of the initial impermeable ice layer. The sub-zero temperature of the soil does not greatly affect the freezing rate or the location of the ice layer, as the latent heat of water is two orders of magnitude higher than its specific heat. The initial frozen moisture content greatly influences the pore space available for flow. The compaction of the soil also affects the formation of the ice layer. In compacted soils the small particles are forced in between the bigger particles, decreasing the average pore dimensions, which increases the pore ice formation.

The conceptual model developed from these results hypothesizes that a fraction of the infiltrated melt water rapidly freezes to the soil grain boundaries. As the coarse grained soil becomes cemented with ice, the water retention characteristics of the soil change as there is a pore space alteration. The pore throats become narrower, and hence the amount of water retained at a specific capillary pressure is increased. The permeability of the soil also decreases, which slows the movement of the water and allows it to freeze earlier in its downward migration. The addition of fine material to a coarse grained soil facilitates the formation of dead end pores which inhibits the downward flow of water. Thus the pore space in a well graded soil becomes saturated with ice at a relatively shallow depth below the soil surface in comparison to gravel that does not contain relatively smaller diameter particles.

The next challenge is the accumulation of more data and analyzing the results in a quantitative fashion, to be able to give specific guidelines for design and implementation of coarse grained engineered structures in cold regions. It is also important to conduct non-destructive experiments to identify and quantify the controlling pore size diameter with regards to pore ice formation, and the location of the pore ice within the pores. A methodology should be developed to quantify the water retention characteristics of a frozen soil.

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